EXPERIMENTAL INVESTIGATION OF THE ENERGY ABSORPTION CAPABILITY OF CONTINUOUS JOINED CRASH BOXES

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ABSTRACT

In the design of vehicle structures for crashworthiness, there is a need for rigid subsystems that guarantee an undeformable survival cell for the passengers and deformable subsystems able to efficiently dissipate the kinetic energy. The front rail is the main deformable component dissipating energy in a frontal crash, which is the most dangerous crash situation, and for which the structural behaviour is mostly affecting.

The design of the front rail, usually consisting of a thin walled prismatic column, requires definition of the geometry, that is, of the shape and dimension of the cross section, of the thickness of the material, and of the material itself.

In this work the analysis of the effect of different cross sections of the front rail, and of the joining system is carried out. Furthermore, the collapse during crash is influenced by the loading rate since the loading speed has substantial influence on the mode of collapse and on the material behaviour. In fact, the structural materials used in this application are known to be strain-rate sensitive.

Within the work, different types of sections are compared. Different non-common continuous joining technologies are examined: three different types of adhesive an acrylic, one component epoxy and two components epoxy and laser welding. Adhesives and laser welding can be used as an alternative to the widely used spot-welding to improve the structure performance due to the continuous joint.

The effects of the loading speed are taken into account by comparing quasi-static crush tests to dynamic impact tests. Dynamic tests have been performed under a drop tower testing apparatus built within the campus of the II Faculty of Engineering of Politecnico di Torino.

1. INTRODUCTION

A very important issue in car design nowadays, is the trend in using new, smart materials. In the next future, well known and widely used materials like deep-drawing steels will be discarded in favor of high-strength steels (dual-phase, TRIP steels…), aluminum alloys, magnesium alloys and various grades of polymeric materials and composites [1-2]. The reasons for this choice are many: the weight reduction to allow for more accessories and safety components, the strengthening of the structure and, last but not least, cost reduction. Moreover, even the lowest priced common steels suffered great costs rise due to increased demand from emerging countries.

Many problems are linked to the introduction of new materials: their properties are still not completely known, the technologies usually adopted sometimes fail, and new environmental and protection problems can arise. Additional problems relate joining systems. For several years car body assembly was fully dominated by spot-welding. Resistance spot-welding is a very cheap and affordable technology to join steel sheets. It is highly customizable, it can be extremely automated, it is very quick, and it does not require preparation of the parts before joining. However, there are also some drawbacks: first, as in all the welding systems there is a heat affected zone that can affect the material strength; second, it is a spot connection system that causes high stress concentrations near the spot, and cannot be used to join different materials (unless very difficult procedures are adopted, whenever possible).

Among the various alternative solutions the most promising are probably laser welding and adhesives.

Laser welding, although still a welding technology, is a continuous joining method. It is yet a very flexible solution that can be easily made automatic by means of robotics. It is even possible to join different metals.

Recent developments in high-power CO_2 lasers and robotic control have accelerated the application of laser beam welding (LW) to vehicle structure fabrication and assembly in the automotive industry. Additionally, it has been shown to offer many advantages if compared with other welding processes: a low heat input, a small heat-affected zone, low welding distortion, welding in an exact and reproducible manner, and welding at high speed. With the advent of new laser technology, such as high power Nd:YAG and CO_2 lasers and fiber-optic beam delivery systems, the automotive industry is re-evaluating manufacturing systems in the body. However, it cannot be used to join other materials like plastics and composites.

The most promising joining solution when dealing with different materials is bonding. The use of structural adhesives in car body construction has a lot of advantages: the joint is not localized in small areas eliminating stress concentrations, the adhesive layer can perform as insulating, protecting and damping material, it is possible to join different materials of almost any kind. The main problems in using adhesives are the loss of strength that comes from the differences in the coefficient of thermal expansion of the adherends and of the adhesive itself (generating residual stresses in it) and their relatively low peel strength. However, up to date structural adhesives have gained very high peel strength sufficient to guarantee very robust designs. Many other, supposed, drawbacks can be worked around by using state-of-the-art knowledge on adhesive joints construction. Surface preparation is little nowadays nor necessary anymore: modern structural adhesives can be applied directly on untreated surfaces, even dirty and greasy. The long curing time can still pose some problems, but, using bonded joint together with other mechanical fastening methods or with provisional fasteners [3], this can be effectively solved: the usual oven treatment for car body paints is then exploited for adhesive polymerization too, if necessary. Probably the main concern in using adhesives, as for many polymer materials, relates to long term endurance, which is still not completely known, especially in severe environments.

There is, maybe, a sort of *cultural* difficulty in designers and manufacturers attitude. They are, comprehensibly, worried by the necessity to introduce dramatic modifications in components design to be suitable for bonding, as it was necessary in the past [4], and expensive changes in manufacturing equipments. As will be shown in the present paper, this is not of concern since recent structural adhesives have so excellent properties to be able to overcome most possible inconvenient.

Main aim of this paper is then to compare results on the use of structural adhesives in structures subjected to crash. Comparison with traditional methods and the obtainable structural improvements have been already demonstrated [4-7]. A wide-ranging comparison, coming from a lot of experimental tests in the Politecnico laboratories, will be addressed here. Three different adhesives and laser-welding technology for joining thin walled metal structures will be considered in the work, and compared to the usual spot-welded solution. Moreover, different sections will be examined to show whether direct substitution of a technology with another one is possible or not, and the greatest advantages of innovative geometries when dealing with new joining methods.

STRUCTURAL COMPONENTS

The basic component addressed in this work is a simplified crash box for frontal impact with square section, made of a common deep-drawing low alloy steel (Figure 1). The steel is DC02 EN10130 (Table 1), and it was chosen on the basis of several considerations: the availability of previous results with the same material [5-6, 8-10] to allow for comparisons, the still relatively widespread use of this steel in car body constructions and, last but not least, accessibility and low cost of this material.

Table 1.
Steel properties

Property	Value
Material	DC02 EN10130
Yield strength, R_e	170-280 (nominal)
Tensile strength, R_m	270-400 (nominal)
Elastic modulus, E	200×10^3 MPa
Plastic modulus, E_p	950 MPa (measured, avg.)
Yield strength, S_y	190 MPa (measured, avg.)

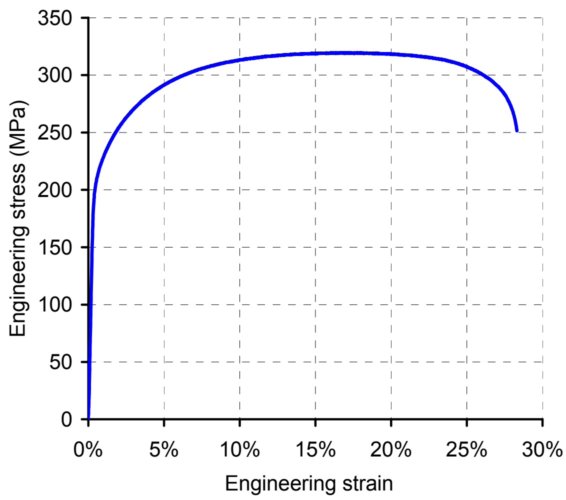
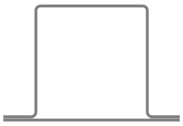
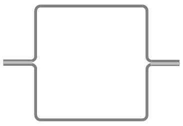
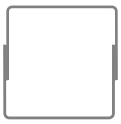
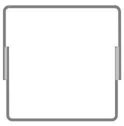
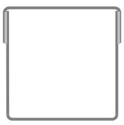


Figure 1. Stress-strain curve for theDC02 steel used in the experimental analysis.

The crash box columns were built by joining two half-shells obtained by plastic deformation. Side of the enclosed square section was 40 mm, and the total length 300 mm for all the examined geometries of the cross section.

When dealing with spot-welds, there are not many possibilities. Since the two face-sheets must be accessible, the box must be provided with flanges (Table 2) and the common solution are as marked with the letter A and B (there are slight variations possible, by shifting the flange position of the B shape with an offset; it is even possible to have asymmetric solution with a different offset in the two flange sides).

Table 2.
Analyzed sections

	Geometry	Spot-weld	Laser	Bonding 330 9514
A		×	×	×
B		×	×	×
C		–	× *	×
D		–	×*	×**
E		–	×*	×**

Note:
*it exhibits some manufacturing problems: it is difficult to fix the two parts of the structure during the welding process.
** it exhibits serious manufacturing problems: when inserting one half shell into the other, there is unavoidable adhesive removal that can bring out incomplete bonding.

Several design configurations for bonded square boxes are possible. Again Table 2 shows some of the possible configurations. Fay and Suthurst [3] examined even more possibilities.

Configurations A and B have some problems when obtained by bonding. Peel loads occur between the flanges, and this can lead to premature failures. Configurations C, D, and E are more suitable for bonding, since an opening load will stress the joint in shear, with reduced peeling.

For laser welding, even if it is theoretically possible to adopt almost all possible configurations, there are in practice many manufacturing constraint. The two sheets to be joined must be clamped together: as a result, only solution A and B can be easily manufactured.

The flanges width in A and B configurations and the sheet superposition in C, D, E were chosen to have the same area (9000 mm²), while maintaining the same square section (40×40×1 mm).

JOINTS CHARACTERISTICS

The characteristics of the spot-welds, adhesives and laser welds are described in the following sections.

Spot-welds

Spot-welded crash boxes were joined by means of 6 mm spots, positioned in the middle of the flanges. The spot pitch was of 30 mm, and it was chosen after careful considerations about the maximum strength allowed and reduction of the peak load. Triggers to start stable collapse were introduced by means of small holes near the top end of the column.

Table 3.
Laser welds characteristics.

Brand and model	Haas HL 3006d,
Working mode	CW, continuous
Beam transport method	Optic fiber, ϕ600 μm
Focusing system	Focusing lens
Pumping system	With lamps
Wavelength λ	1064 Nm
Max output power	4000 W
Max work power	3000 W
BPP	25 mm×mrad

Laser-welds

Most known industrial laser sources are CO_2 and Nd:YAG. The first type of lasers is used in light constructions, with penetration depth less than 10 mm. The second type is used for small sized components with limited thickness because of the small spot size. In this work the sheets, 1mm thick, were joined by means of an Nd:YAG laser source.

The used laser was a Haas HL 3006d. Its main characteristics are reported in Table 3 (Figure 2).

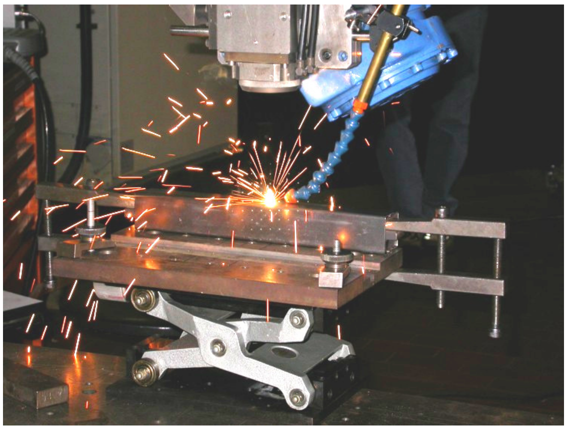


Figure 2. Laser joining of one of the analyzed samples

Adhesives

After a selection phase, taking into consideration previous experiences [5-6, 11] made with various kinds of adhesives, including Araldite®, Dow® and various Loctite®, three types were chosen:

- a urethane metacrylate ester, Loctite® 330 Multibond
- an epoxy resin, Loctite® Hysol® 9466
- an epoxy resin, Loctite® Hysol® 9514

Nominal strength of these adhesive are summarized in Table 4.

Table 4.
Nominal strength of the used adhesives.

Adhesive	Shear strength, MPa (ASTM D1002-94)	Peel strength, kN (ASTM D1876-95)
Loctite® 330 Multibond	16 ÷ 22	1.1 ÷ 1.2
Loctite® Hysol® 9514	52 ÷ 53	4.8 ÷ 5.7
(Loctite® Hysol® 9466)	30 ÷ 39	0.6 ÷ 0.8

The acrylic ester 330 Multibond is a general purpose structural adhesive with good characteristics. Differently from traditional acrylic adhesives it has a much greater toughness that makes it useful for energy absorbing applications. Nominal shear strength according to ASTM D1002 is 15 ÷ 30 MPa, whereas tensile peel strength (DIN 53288) is 12 ÷ 22 MPa. Main limitation of this adhesive is the low temperature applicability: since it is for curing at ambient temperature, maximum operational temperature is relatively low (120°C, but with progressive loss of strength already from 60°C).

The Hysol 9514 epoxy is a high performance structural adhesive. Shear strength can be up to 45 MPa (depending on adherends), with a peel strength of 9 MPa. Temperature limit is quite high: strength reduction is important only above 120°C. It has superior performance with respect to Hysol 9466 that was initially considered.

A series of preliminary tests on the used adhesives were performed to measure the strength obtained with the specific sheet material. Shear strength single-lap tests (Figure 3), and T-peel strength tests (Figure 4), were performed.

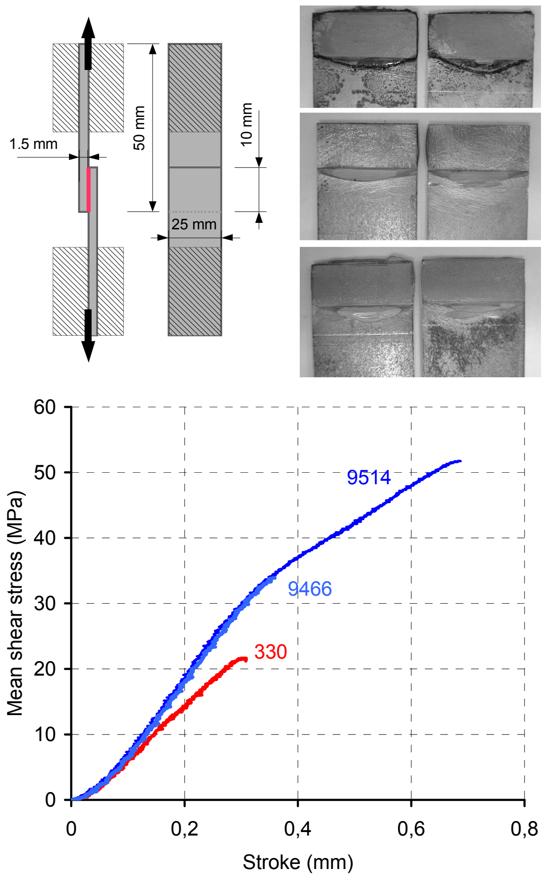


Figure 3. Shear strength tests.

Shear tests were not performed according to ASTM standard, because the strength of the adhesive was in excess of the strength of the steel. In this case a specimen with only 250 mm² bonded area, instead of 625 mm², was used (25 mm wide, 10 mm superposition length; the bonded pieces were 1.5 thick, 50 mm long).

All the adhesives showed cohesive type failures, resulting in very high strength and capacity of energy absorption. However, Hysol 9514 was found much better especially in terms of peel strength: the increase, with respect to the other adhesives, is from 300% up to 400%.

The Hysol 9466 has not been successfully used in crushing tests because some preliminary samples put in evidence a too brittle behavior of the adhesive and a reduced capacity of plastic deformations.

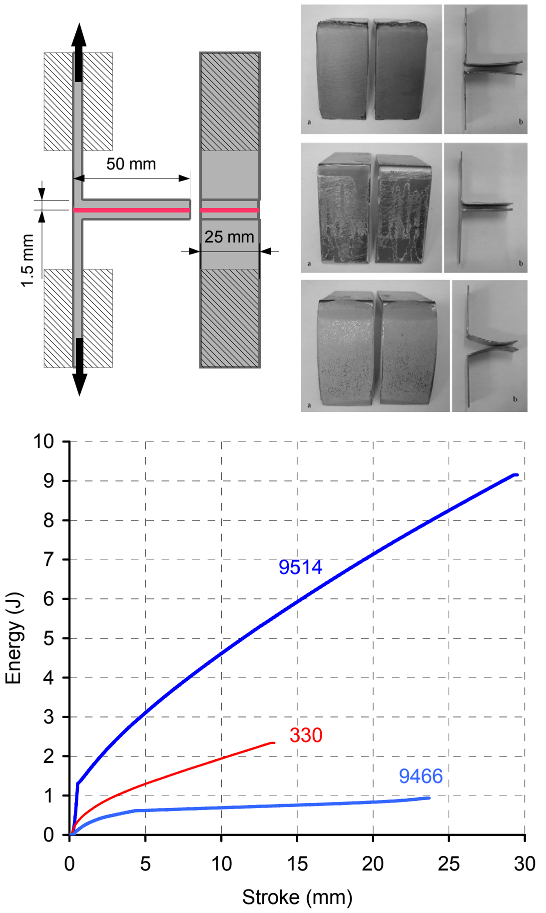


Figure 4. Peel strength tests.

EXPERIMENTAL TESTS

A series of experimental tests in axial compression was performed on the square box columns.

Some quasi-static and dynamic impact tests were performed. Even if the chart will show results of single, representative tests, several repetitions were done for each case. Over 100 tests were performed.

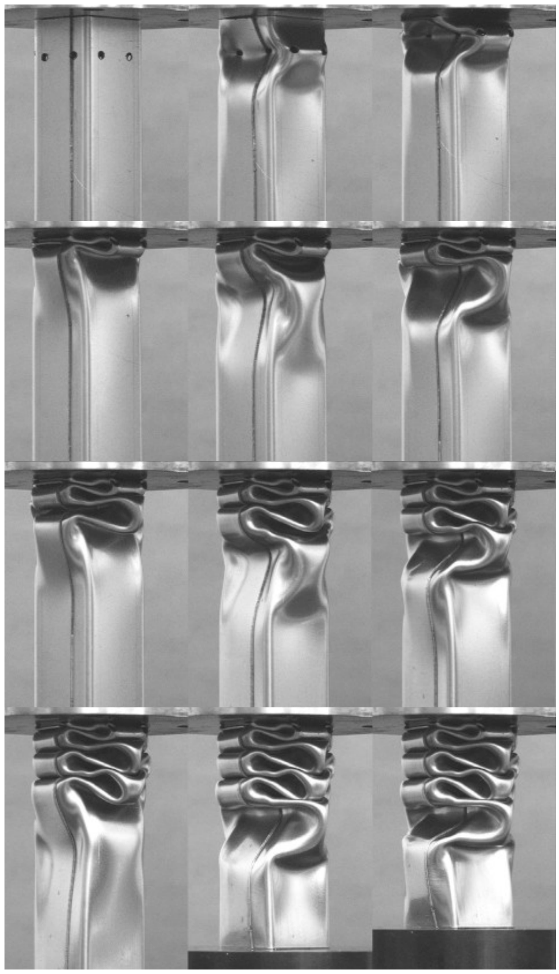


Figure 5. Crushing sequence of a bonded column, quasi-static loading, C solution.

Quasi-static tests (Figure 5) were performed by means of a general purpose hydraulic material testing machine (DARTEC HA100, 100 kN maximum load, 100 mm/s maximum speed). The specimens were placed centrally in the test machine, without any further support, and between two very hard steel end plates, which were bolted to the crossheads of the testing machine. The compressive force was recorded during crushing, together with the crosshead displacement, giving a load-stroke curve of the crushing process. The quasi static tests were stopped after reaching a prescribed crushing distance which was approximately 200 mm. The expected structural behavior of a thin-walled beam submitted to an axial load is a progressive collapse characterized by the regular progressive formation of plastic folds.

Figure 5 shows a pictorial sequence of progressive folding during a quasi-static crushing test.

Adhesively bonded crash boxes

Both solutions A and C performed quite satisfactorily (Figures 6 to 9). However, due to the inferior peel strength, some problems of debonding were encountered with Multibond 330 in configuration A.

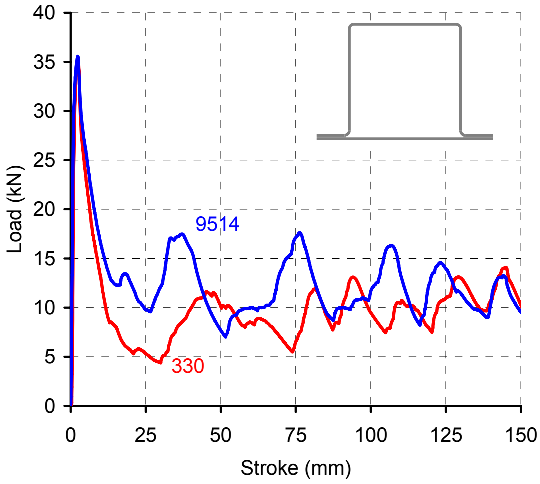


Figure 6. Quasi-static tests comparison, load-stroke curves for A specimen and the two adhesives, without trigger.

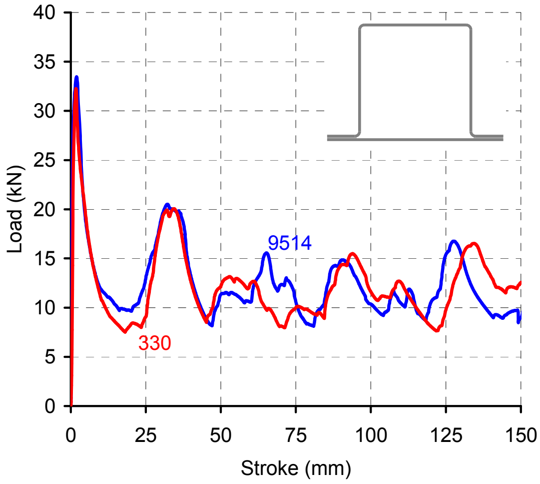


Figure 7. Quasi-static tests comparison, load-stroke curves for A specimen and two adhesives, with trigger.

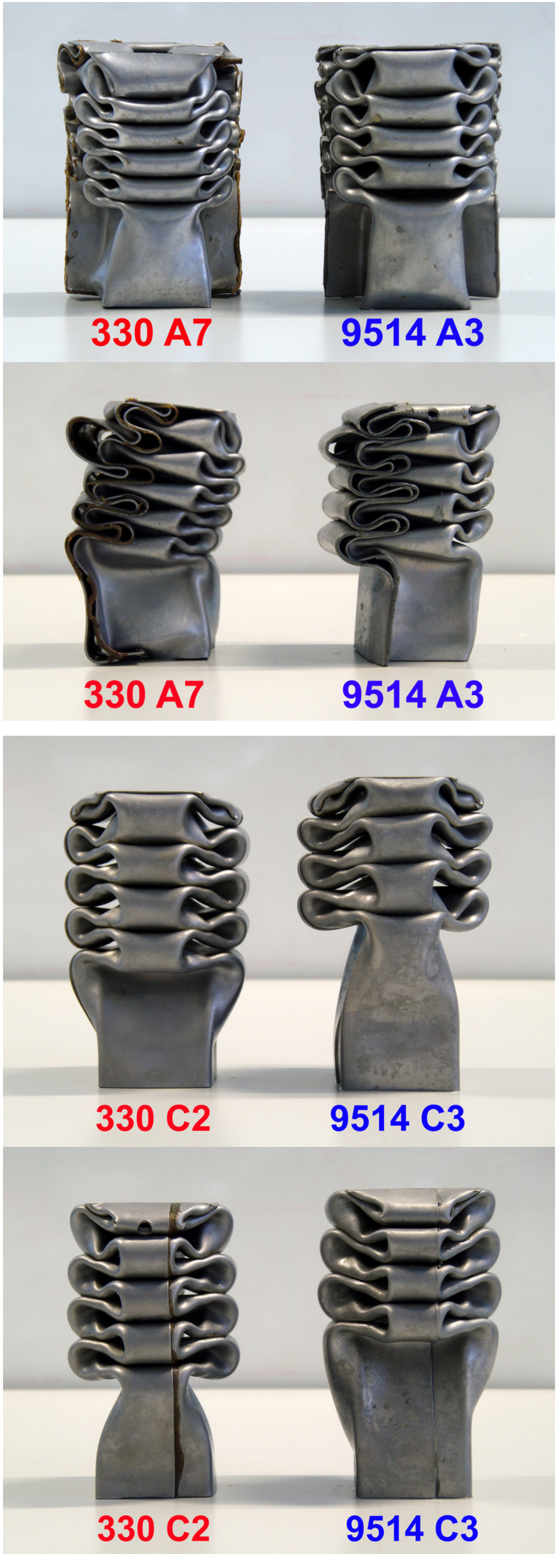


Figure 8. Folding patterns (views from two sides) in quasi-static tests on bonded crash box columns (A and C geometry).

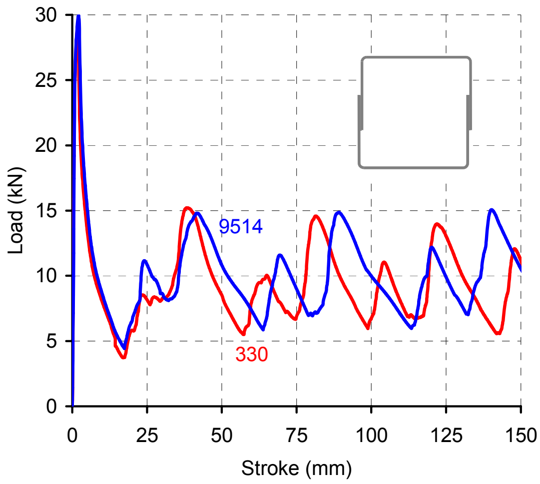


Figure 9. Quasi-static tests comparison, load-stroke curves for C specimen and two adhesives.

This caused a 30% energy absorption reduction. By triggering the initial collapse phase by means of a series of transverse holes at the top of the column, this problem was avoided: the difference was then reduced to some small percent.

The alternatives for overlapped bonded columns were as indicated in Table 2 as C, D, and E. Solution C is simpler and easier to bond: in fact D and E exhibit serious manufacturing problems: when inserting one half shell into the other there is unavoidable adhesive removal that can bring out incomplete bonding. From the structural point of view the differences are not significant.

Also for configuration C, triggering gave improvement in efficiency.

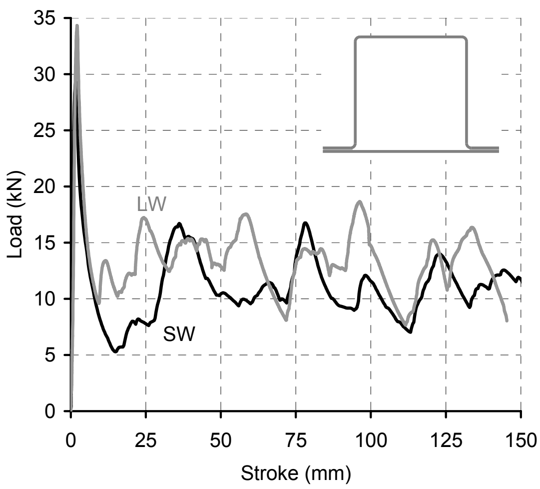


Figure 10. Load-stroke curves for LW and SW crash boxes, A solution.

The final result was that almost no difference was found in the two configurations, with both adhesives. Avoiding debonding, the crash boxes behave very well in quasi-static compression, with very regular folding pattern, as shown in Figures 5 and 8.

Differently from Figure 6 samples, all the test results reported in following paragraphs are about triggered samples.

Laser welded and spot-welded crash boxes

Laser welded and spot-welded columns were also tested under quasi-static compression loading. The results in terms of the load-stroke curves and folding patterns are reported in Figures 10 to 13.

Generally speaking, the spot welds and laser weld resisted the loading and deformation well. There was no interfacial failure of the weld.

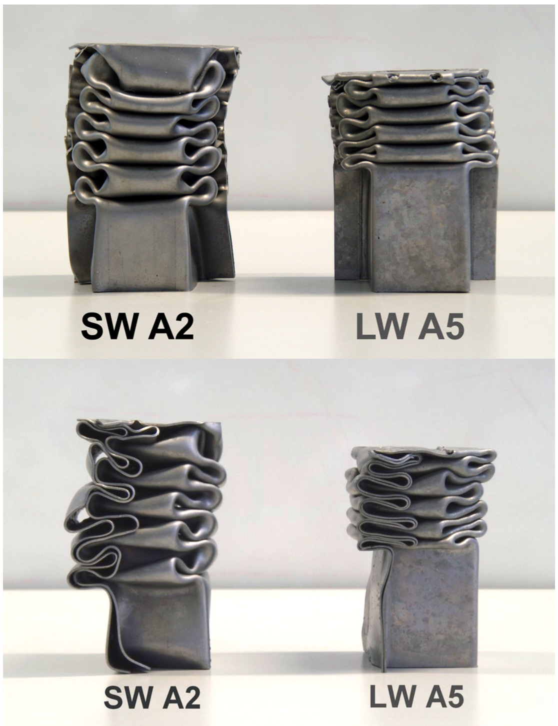


Figure 11. Folding patterns in quasi-static tests on spot welded and laser welded crash box columns, A solution.

For A and B configuration, laser welding produces a folding length shorter than spot welding.

In the laser welded structures the energy absorption is higher also because much material of the flanges collaborates to the crushing resistance (Figures 11-14).

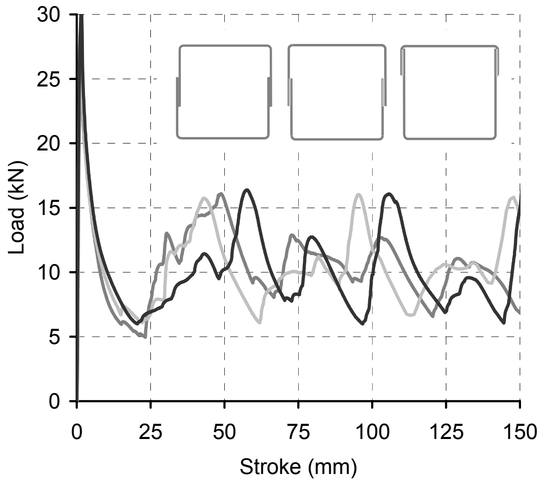


Figure 12. Load-stroke comparison for three laser-welded solutions C, D, and E.

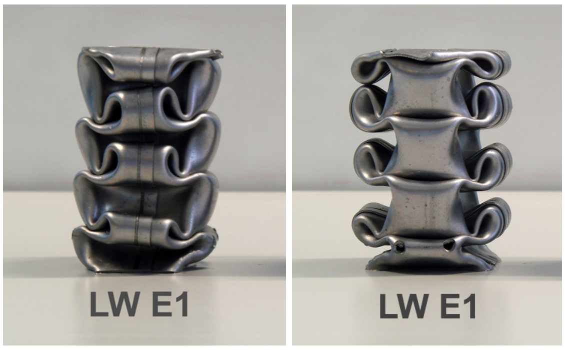


Figure 13. Folding patterns in quasi-static tests on laser-welded E crash box columns.

A simple observation of Figure 10 makes clear the advantage in laser-welding versus spot-welding: the first joining method gives more energy absorption capability and more stable collapse.

This is also clear from Figure 11, in which two crushed boxes are compared: the laser-welded one gave a very regular folding patter with a shortest fold length, which is advantageous for energy absorption. Figure 12 reports the results on tests on C, D and E configuration for laser welded samples. Even if the folding pattern is a little bit different for the three solutions and with respect to the bonded solutions, the energy absorption is almost the same.

In Figure 13 a laser-welded E type column is shown. The collapse is still very regular and stable, however if compared with the bonded C solution in Figure 9, it appears that the E laser-welded has a longer fold pattern

Figure 14. Folding pattern in quasi-static tests on laser-welded and bonded crash box columns.

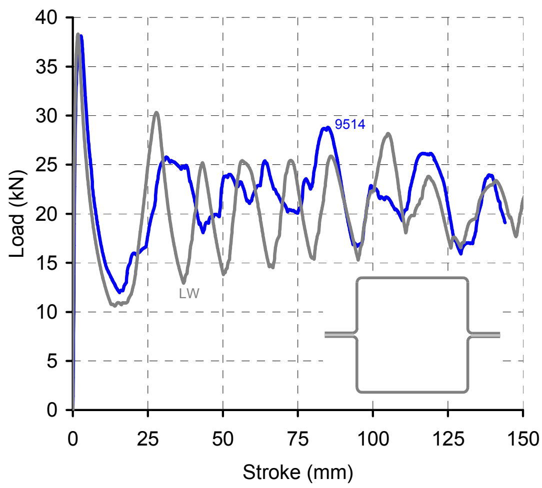


Figure 15. Comparison of laser-welded and bonded crash box columns, B solution.

Figure 14 shows a comparison of the laser welded solution with the adhesively bonded one. Even if there are substantial differences, especially in the first collapse, the bonded solution assure a more uniform load during collapse. The average load is also slightly higher (Figure 15).

Impact tests

Impact tests were performed with a drop tower device installed at the II Faculty of Engineering of Politecnico di Torino (Figure 16). This falling weight test device [3, 9-10] has a drop height of 12 m and a maximum speed of 13 m/s approximately.

The falling mass could be adjusted in small step up to a maximum value of 200 kg.

The falling mass does not impact directly on the specimen: the crushing action is guided by a special rig (Figure 17).

No end constraints were provided to the specimen and special care was taken to provide flat parallel faces of the specimen and test rig.

The load is measured with PCB piezoelectric load cells, the stroke with an optoelectronic encoder.

Figure 16. Twelve meter drop tower for impact tests.

All impact tests were conducted at ambient temperature and the drop height and drop mass were adjusted to crush test specimens by approximately 50-70% of their initial length with speed of 10 m/s.

The importance of triggering was much greater than in quasi-static tests. In some cases, with configuration A namely, transverse holes were not sufficient. Some rivets added at the top of the column helped in reducing debonding.

If debonding is avoided, the two adhesives give similar results, and the folding pattern is sufficiently regular (Figure 18).

Configuration B was found less problematic, as expected. Transverse holes were sufficient to initiate a very regular folding (Figure 19). It comes out that the two adhesives perform quite the same way.

Figures 20 and 21 show a comprehensive comparison of joining methods and types of sections in dynamic impact conditions (thick line) compared to static test results (thin line).

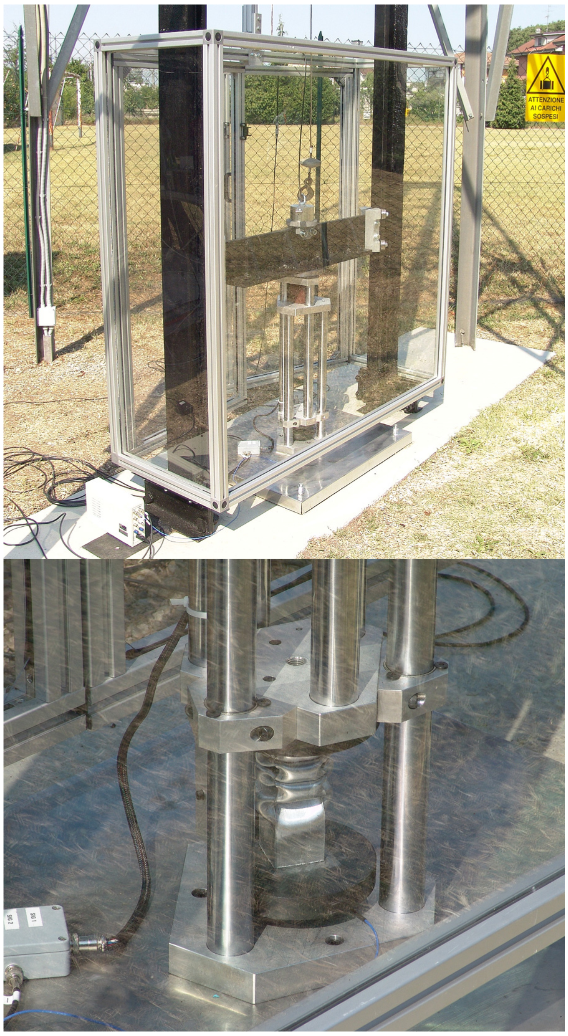
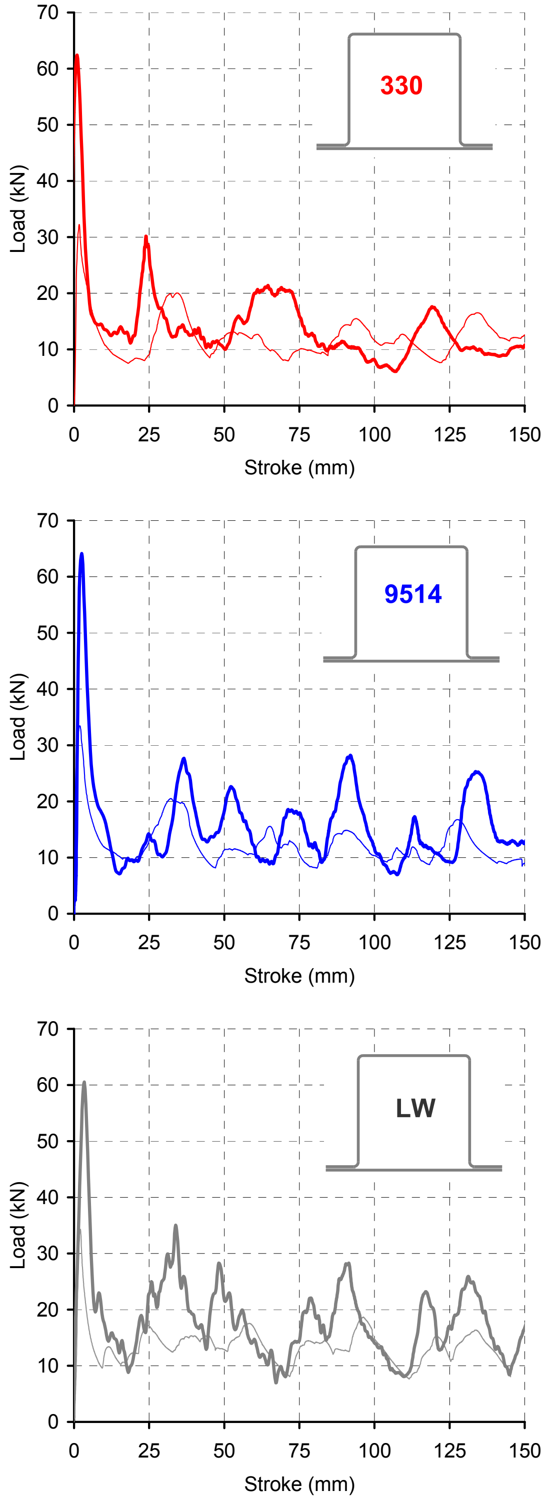


Figure 17. Impact test rig.



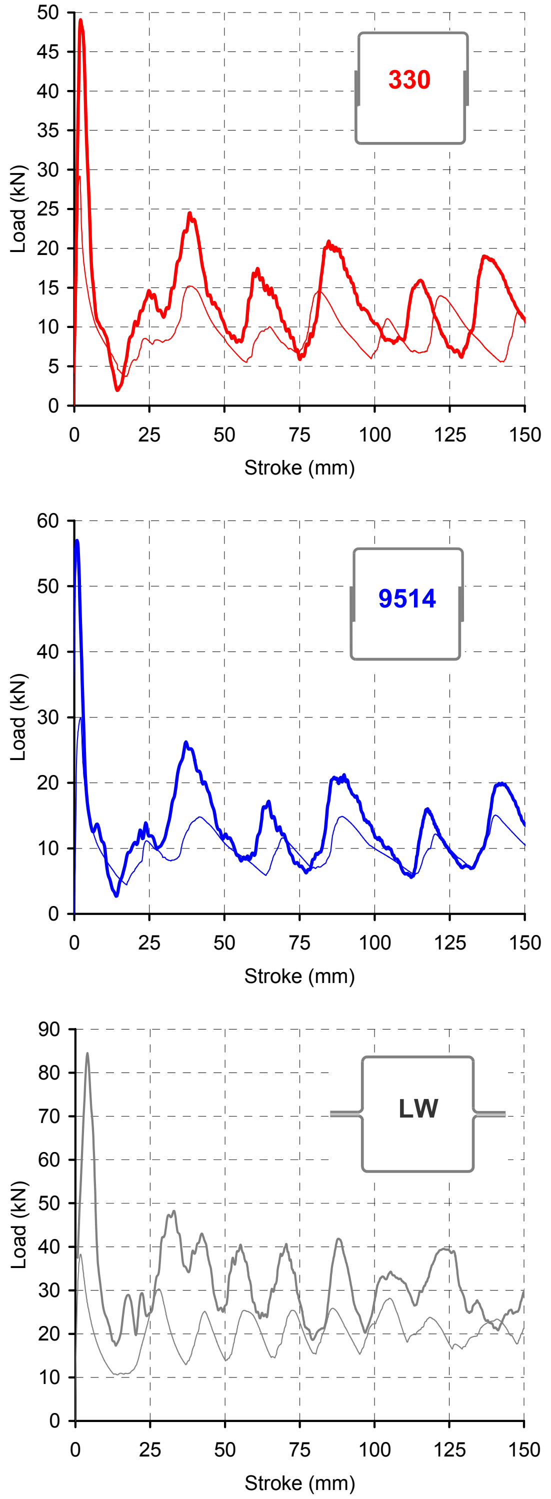


Figure 20. Test results for top-hat A solution: impact loading vs. static.

Figure 21. Test results for top-hat B and C solution: impact loading vs. static.

Figure 18. Dynamic, impact tests on crash box columns, configuration A, 9514 adhesives.

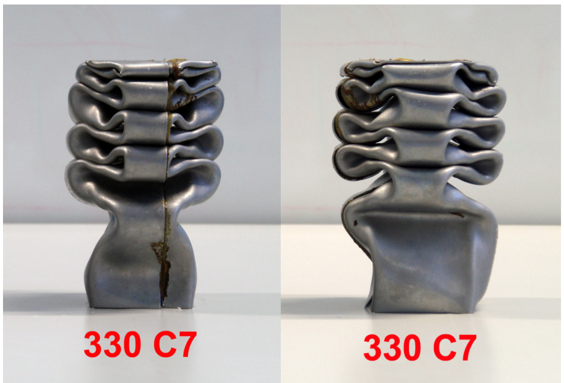


Figure 19. Dynamic, impact tests on crash box columns, configuration C, 330 adhesives.

In general terms, in all tests the diagram of the crushing force is that typical for thin-walled beams.

It can be observed that the crushing force increases significantly with the test speed, although it is important to remember that static tests are performed at a constant velocity, while dynamic tests are impact tests at non constant velocity (the initial velocity is progressively reduced by the energy absorption). The DC02 steel used for the beam construction is a strain-rate sensitive material and this fact can explain this increment of the force values. All the dynamic tests indicated a strong influence of the loading speed on the components behavior.

For all solutions and for the three different joining technologies there is a significant increase in energy absorption of the crash-box with speed (Figures 20-21). If the joining does not fail (as in some A bonded sample) the folding pattern in static and dynamic tests is quite similar. Continuous joining technology (LW and bonding) usually produce a regular crushing with energy absorption greater than spot-welded solution. The energy absorption obtained with this two techniques and the same geometry is similar.

C, D and E geometries, thanks to the absence of flanges, produce very regular and progressive folding pattern in static and dynamic condition. However, if the collapse is regular, the energy absorption is greater for A and B solution due to a smaller folding length and a greater cross section. Even considering the specific energy (energy/weight), the A and B solutions are more efficient than C, D and E.

Comparison of the joining methods

The comparison of the results found with two analyzed configurations, and with the two adhesives (the 9466 was discarded due to its scarce strength especially in peeling) is shown in Figures 6 to 9. All the geometries of bonding were found acceptable, provided that proper measures are taken to avoid unstable collapse.

The comparison of spot-weld and laser-weld for this application is in Figures 10-11. Laser-welding is superior both in terms of stability and energy absorption. Laser-welding can substitute spot-welding without many changes, except the equipment to make the welds.

Then the comparison with impact tests is shown in Figures 20 and 21, for two adhesives and laser-welding. Spot-welded columns were not reported in impact testing conditions, since it was clear the advantage with bonding or laser-welding.

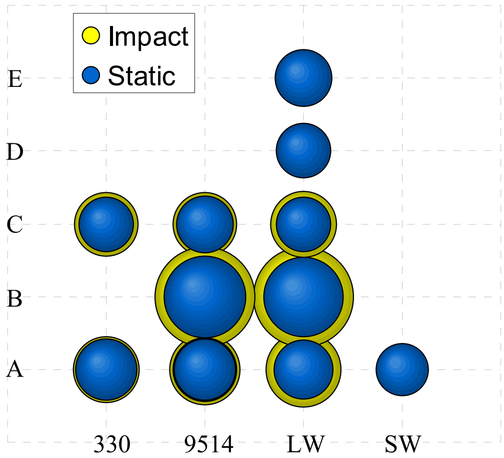


Figure 22. Summary of the results from the different joining methods and geometry in terms of the average crush load

As previously said, for configuration A, provided that a proper folding initialization is achieved, the two adhesives behave similarly both in quasi-static and impact conditions. Looking at the energy absorption it comes out that there is a 20% dynamic increase, mainly due to the strain-rate sensitivity of this material [9].

Equivalent results were obtained with configuration B. The dynamic effect, in this case, is even greater (around 35%).

In both cases Hysol 9514 behaved better than Multibond 330 but differences are, depending on the case, of a few percent (namely, from 1% to 11%).

In Figure 22 a graphical representation of the most significant results in terms of average load is shown. Average load is a good indicator of energy absorption capability. The chart indicates the average load as the size of the bubbles. The joining method is the abscissa, while the ordinate represents the geometry of the section. It comes out that laser-welding is the more efficient solution for energy absorption. However, all joining methods are comparable, and better than spot-welding. Despite the trend to minor stability of the geometry without flanges, greater energy absorption comes still from geometries with flanges (A and B).

Therefore, there are many alternative efficient solutions to spot-welding that can give valid solutions to the problems posed by new car construction technologies (new materials, joining different materials).

CONCLUSIONS

The behavior of square box bonded columns subjected to axial crushing was investigated. A couple of up to date high performance structural adhesives and the laser-welding technology were compared to classical spot-welding.

Main objective of the work was to demonstrate the advantages of using adhesive bonding and continuous welding in structures subjected to crash, and that very efficient structures with high capacity of energy absorption can be obtained. Moreover, this result can be obtained without additional effort in terms of preparation of the components, surface treatment, etc.

Five series of square boxes were considered: a classical top-hat section, a double-hat section, and three variations of closed square obtained by joining two C shaped half-shells on the sides.

When appropriate countermeasures are provided to avoid debonding, mainly by triggering and, in some cases, adding some additional fasteners like rivets, the top-hat solution has more or less the same performance. This is an important practical result: for instance in car manufacturing it is not necessary to fully redesign the closed section thin walled parts of the car body. At the same time, if debonding can be avoided, even a weaker adhesive can give excellent results. The advantage lies in the fact that the adhesive gives a continuous connection of the sheets, with much more energy absorption. Impact affects negatively the bonded column behavior: debonding is much likely to occur, and proper countermeasures are extremely important to avoid catastrophic failure, with very little energy absorption.

Laser-welding is another very interesting solution: it gives results similar or even better when compared to spot-welding, and results similar to adhesive bonding. Stability is usually much improved with laser-welding compared to the all the other joining solutions.

In conclusion, nowadays many joining solutions for structures and components subjected to crash loading are available. They can give better performance or irreplaceable solution to joining problems (e.g. different materials), and this without the past problems that prevented their use (pre-treatment or cleaning of the surfaces, important design changes).

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